Volume 34
Number 520 *Estimation of soil moisture under corn*

Article 1

December 1963

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Estimation of Soil Moisture Under Corn

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RESEARCH BULLETIN 520 DECEMBER 1963 AMES, IOWA

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SUMMARY

This study was undertaken as an attempt to develop a simplified approach to a complex problem—the prediction of soil moisture under corn which, at times, may have a limited moisture supply. Soil moisture under corn was estimated for June, early August and early November by using April, June and August soil-moisture survey data as the starting points. All computations were made on the basis of the amount of plant-available water present. To obtain this value, both the field capacity and the wilting point of a soil need to be known. Precipitation amounts were added to the data for soil moisture supply after deducting a value for runoff. An antecedent precipitation index, which varied with the season, was used to compute runoff.

For the April-June period, evaporation was estimated as 0.1 inch per day for as long as any available water was present in the top 6 inches. After early June, evapotranspiration was estimated by using open-pan evaporation data as the measure of the potential for evaporation. This was multiplied by a factor to account for crop development and, when necessary, by a factor that considered any moisture stress present. The product of these values gave the actual evapotranspiration for each day. The water used in evapotranspiration was removed from the shallow depths early in the season, with a gradual increase in the depth of extraction as the season progressed. By Aug. 1, water use was assumed to take place to a depth of 5-feet. Water use was apportioned among the different depths active in water absorption, with the largest percentage coming from the shallow depths.

For the April-June period, the correlation between the observed and the predicted soil moisture was 0.96. The linear regression was

$$Y = 0.49 + 0.94X$$

where the observed soil moisture was X, and the predicted soil moisture, Y. The standard deviation from regression was 0.70 inch. The procedure underestimated the soil moisture in the top foot by an average of 0.13 inch and overestimated the amount in the second foot by 0.16 inch. The three deepest foot-increments were estimated to be 0.10 inch or less from the observed value.

For the June-August period, the correlation between the observed and predicted soil moisture was 0.95. The linear regression was

$$Y = 0.34 + 0.94X.$$

The standard deviation from regression was 0.84 inch. The estimated soil moisture for each foot-increment averaged 0.10 inch or less from the observed value.

For the August-November period, the correlation between the observed and predicted soil moisture was 0.96. The linear regression was

$$Y = 0.38 + 0.92X.$$

The standard deviation from regression was 0.85 inch. The average difference between the observed and estimated soil moisture in each foot was less than 0.10 inch.

Estimation of Soil Moisture Under Corn[1]

by R. H. Shaw[2]

Although numerous references can be found in the literature relating to different methods of predicting evaporation and evapotranspiration, there has been relatively little research on predicting soil moisture under a row crop such as corn. This study was an attempt to develop a simplified approach to a complex problem—the prediction of soil moisture under an annual row crop which does not give a complete ground cover, where the soil surface is sometimes dry and where soil moisture may at times be limiting. As a further complication, it was also necessary to estimate runoff.

In selecting the "best" method to estimate potential evapotranspiration,[3] one is frequently confronted with a paucity of information relating these methods to accurate water-loss data.

Some of the prediction methods appear to have general application; others are extremely limited in use. The accuracy of the Blaney-Criddle (1), Thornthwaite (12) and Penman (9) methods has been checked against Iowa pond and open-pan evaporation (15, 16), and the Thornthwaite and Penman methods also have been checked against evapotranspiration from a meadow cover (2). Both the Thornthwaite and Blaney-Criddle methods provide a simplified approach for estimating evapotranspiration, but these methods have a considerably reduced accuracy for short-period observations. Penman's method requires considerably more data, some of which is available at only a few weather stations, and requires more computation time than the other methods. The Penman method, however, was found to be the most accurate of the methods tested (2, 9).

[1] Project 1276 of the Iowa Agricultural and Home Economics Experiment Station, U.S. Weather Bureau cooperating. This work was partially supported under Weather Bureau Contract Cwb-9560. The author wishes to acknowledge the work done by Mr. Stan Buss, which laid the foundation for this study. This computation has now been programmed for the IBM 7074 by the Iowa State University Computation Center.

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[3] Potential evapotranspiration has been defined by the Commission for Agricultural Meteorology of the World Meteorological Organization as the amount of water vapor that evaporates from the soil-air interface and from plants when the soil is at field capacity. In some definitions, this is expanded to require an actively growing crop which completely covers the ground surface.

In developing a technique for predicting soil-moisture changes, it was believed that the method should be relatively simple to use but still as accurate as possible. Results of an earlier study (2) showed that soil moisture could be predicted as accurately by using Class A evaporation-pan data for the evaporation potential as by using Penman's equation. Evaporation-pan data are recorded at relatively few weather stations, but these data are available for a period of years in the climatological records (13). The evaporation-pan network in Iowa and the immediately surrounding area was dense enough so that open-pan evaporation could be evaluated for different parts of the state. Evaporation pan data provide an evaluation of the meteorological factors causing evaporation—that is, the evaporation potential. However, evaporation pans have a different type of surface than does a crop cover and, at times, represent a wet area surrounded by a large, relatively dry area. The pan data used here were not adjusted for surface temperature. This may account for some of the variations found between years. The study reported here was conducted by using the evaporation-pan data as the measure of the evaporation potential, but the study could have utilized any of the methods available for estimating evaporation potential.

The soil-moisture data used to check the accuracy of the soil-moisture prediction method were obtained from the Iowa state soil-moisture survey, which has usually been conducted four times a year since its inauguration in 1954. These surveys provide soil-moisture data for April, June, August and November and provide starting and final soil-moisture values for the periods April to June, June to August and August to November.

The range of years and locations gives a broad sample of Iowa weather conditions and soil types (fig. 1). The survey sites have little or no slope but are located so that surface water will drain

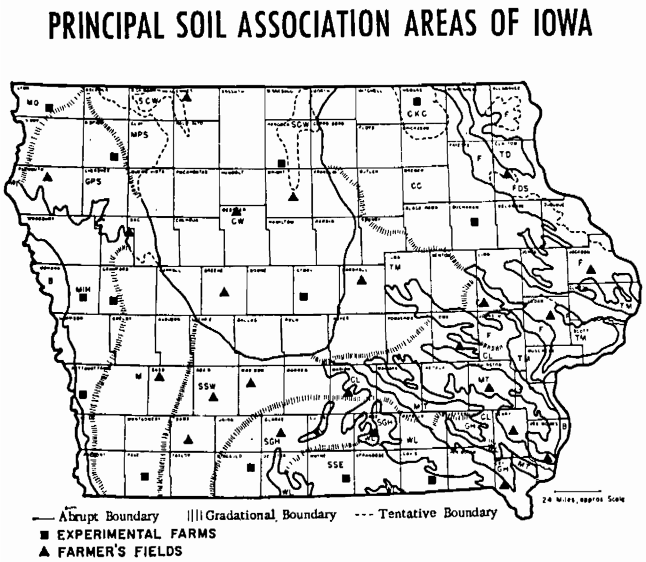

Fig. 1. Location of soil moisture survey sampling sites.

away from the area. Except for very wet periods, there is no standing water on the sites. Low spots were purposely avoided to remove this problem as much as possible. On occasion, since the survey was started, standing surface water has occurred, and water tables have been found in the 5-foot profile.

In considering the accuracy of a soil moisture prediction method, it is important to evaluate the sampling errors involved in the data. On each date at which soil-moisture samples were taken, six borings were made by 1-foot increments from the surface to a depth of 5 feet in a 40 by 40 foot area. The available soil moisture was determined from these samples. Extensive samples taken in a variable glacial till soil in central Iowa (11) were used to estimate the sampling error in the moisture survey. Values of the standard error of the mean are presented in table 1. These values are believed to represent values near the upper limit of variability that would be encountered on most soils. Although the upper layers have a higher mean soil moisture, they are more uniform and have the lowest standard error. On some of the loess soils in Iowa, it is believed that the error for each foot is near that for the top foot shown in table 1 and that the error for the 5-foot profile would be considerably less —possibly near 0.5 inch.

Table 1. Standard error of the mean soil moisture based on six samples per plot in a glacial till soil, Webster silty clay loam, Ames, Iowa, 1954.

Depth (feet)	Standard error of the mean (inches)
0-1	0.18
1-2	0.22
2-3	0.31
3-4	0.47
4-5	0.48
0-5	1.2

All available data were carefully checked to eliminate observations that had obvious errors or in which factors other than those considered here may have entered into the results. In a few areas, ponding of water occurred in very wet periods, or underground water movement may have influenced the results. In some instances, changes in soil moisture between different sampling dates appeared to be physically impossible. These errors are part of the sampling error, and such sites were omitted when testing the prediction technique. At a few sites, rainfall was recorded a few miles from the plots. If the Iowa climatological data indicated that the total rainfall for any test month showed a noticable gradient in the area of a particular site, this site was omitted. These sites were used when a gradient was not present, but they usually showed more variability between actual and predicted values than did those sites where rainfall was recorded at the sampling site.

For each test period, a soil-moisture sample was used as the starting point. All values were converted to inches of plant-available water by subtracting the moisture at the wilting point from the moisture obtained at the sampling date. This gave the available water in each foot of the 5-foot profile. The estimate for the end of the period, as obtained by the prediction technique, was compared with the actual soil moisture at the end of the period to check the accuracy of the technique. The technique varied somewhat between the periods because of the different factors used in computing the water balance.

METHODS

Several factors must be considered in estimating soil moisture. The field capacity of the soil must be estimated. This is not the saturated condition of the soil, when all air and capillary spaces are filled with water, but is the condition existing after a saturated soil is permitted to drain for a few days until only the capillary spaces are filled. The wilting point must also be estimated, since all computations are done on the plant-available water. The runoff must be predicted to estimate the amount of water that entered the soil. A means for estimating potential evapotranspiration is necessary, and adjustments must be made for stage of crop development, for dryness of surface soil and for soil-moisture limitations for the plants.

Field Capacity

A field-capacity value must be set to determine how much water can be held in each foot of the 5-foot profile. Since there is no satisfactory laboratory method to determine this value, it is best determined in the field. For some soils, experiments were conducted to determine field capacity. For others, the value used was based on the survey data. Field sampling has shown that this value will vary with the season, probably because of temperature effects. In this study, field capacity was considered to be the upper limit of the soil moisture measured in the field (excluding the April survey) except for certain special conditions. Exceptions included the presence of a water table or the lack of time for precipitation to percolate through the profile.

Water which percolates into the soil does not immediately move through the profile. For this study, it was assumed that percolating water takes 3 days to move through the profile and that the water above field capacity is removed at the rate of one-third of the amount each day. For example, if the entire profile was above field capacity, excess water from rains within 3 days was considered to percolate out of the profile at the rate of one-third of the amount for each day after the rains. If only the upper layers were above field capacity, the excess water resulting from recent rains percolated to deeper depths at the same rate. In all cases it was assumed that a given foot-increment must have reached field capacity before any water moved through it. An adjustment for recent rains was used only to account for precipitation just before sampling. At other times, water in excess of field capacity was assumed to have immediately percolated through the profile or saturated layers. Although not strictly valid, this procedure simplified the computations.

On the April sampling date, moisture in the top foot was frequently higher than the estimated field-capacity value. In this case, this value was set as the revised field capacity for the April-June period only, after allowance was made for recent rains to percolate to deeper depths. This condition was usually a result of cold soil temperatures and, in a few cases, frost layers, which may be encountered in early spring. Sampling should be delayed until the soil has been frost free for several days.

When free water was found in the profile at the start of any period, an accurate prediction of soil moisture could not be made. The disappearance of free water is affected by factors other than those considered here. The only situations that showed any consistency were those when free water was present in June and when no percolation had occurred through the top foot for at least 4 weeks before the August sampling. Under these conditions, the usual field-capacity values could be used in August. In the data presented here, all sites were omitted where free water was present in the profile on the first sampling date for the period.

Wilting Point

The wilting point was set equal to the 15-atmosphere percentage for all soils. Field sampling of dry soils indicated that this gave a very close approximation of the moisture value to which plants could reduce soil moisture.

Estimating Runoff

Runoff must be computed for each daily precipitation amount. Kohler and Linsley (5) have presented a graphic estimation of runoff, based on watershed data, in the form of a hyper-dimensional diagram showing the relationship between runoff and several runoff-producing factors. Using this information for the late June period and storm duration zero, Buss and Shaw (2) developed fig. 2, which gives runoff as a function of rainfall and the antecedent precipitation index (API). The antecedent precipitation index was given as

$$API = P_1/d_1 + P_2/d_2 + \ldots + P_i/d_i \quad (1)$$

where P_i is the amount of precipitation that occurred i days prior to the day being considered, and d_i is the corresponding number of days.

Buss (2) developed this method from 1954 data. He found that if the top 3 feet, or more, were at field capacity, a correction for excess runoff was necessary. An examination of several years' data indicated that this occurred during certain seasons when heavy rainfall amounts were measured. During summer months of wet years, use of fig. 1 resulted in a consistently high soil-moisture value when rains occurred. To avoid overcorrection for small rains, and to allow for greater runoff from heavy rains, the precipitation index was modified to allow greater runoff for rains of 1 inch or more. For all rains of 1

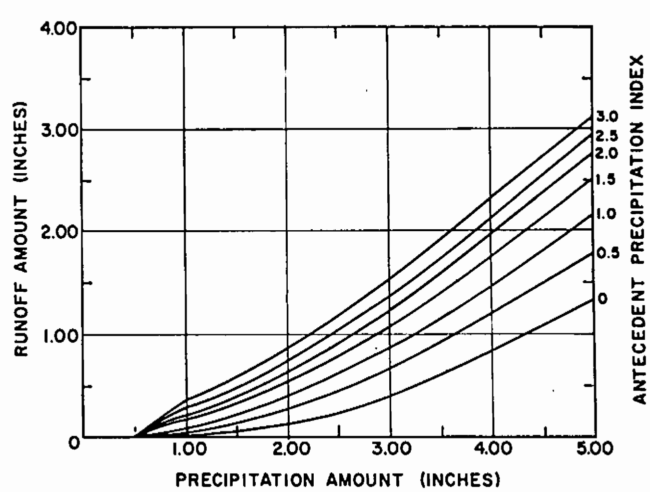

Fig. 2. Prediction of runoff from precipitation and antecedent precipitation index (after Buss and Shaw, 2).

inch or more, half of the precipitation amount was added to the index for the day having more than 1 inch of rainfall. This procedure gave the revised index

$$API = P_1/d_1 + P_2/d_2 + \dots + P_i/d_i + P_o/2 \quad (2)$$

where P_o is the precipitation amount for which runoff was being computed. The P_0 term was used only when the precipitation was 1 inch or greater. This term was zero if the precipitation was less than 1 inch. On subsequent days $P_o/2$ was carried in the expression as P_i.

This revision could have been accomplished by revising fig. 2, but, since the index is empirical and the revised index is used only part of the year, the above modification was considered the simplest to make.

Equation 2 was used to predict runoff in the spring when the ground is bare or cover is sparse and in the summer when high-intensity rains are expected to occur. After Aug. 31, the combination of a good crop cover and low-intensity rains was assumed to result in less runoff, and runoff was computed according to equation 1.

Evaporation and Evapotranspiration Loss

The procedure used to predict the water vapor loss depends upon the time of the season and the stage of crop development.

April through June 6[4]

The ground condition during the spring period may vary. The residue from a previous crop, for example, may still remain on the surface of unplowed ground, a meadow crop may not yet be plowed under, the surface may have been plowed or ground recently planted to corn may have a very sparse ground cover. Therefore, all water loss was assumed to take place from the top 6 inches of the soil, whether by evaporation from the soil or by transpiration through the small plants. Under meadow existing for a short time early in the period this assumption is not entirely correct. However, because vapor loss at this time is largely from the top 6 inches and the computation is much simpler, this assumption was made. The available water in the top foot at the start of the period was assumed to be evenly distributed. If held in an uneven amount, the extra 0.1 inch was put in the top 6 inches.

Solar radiation is relatively high during much of this period (14). The availability of water for evaporation is believed to be the prime factor that limits water loss. As a first approximation, water loss by evaporation and transpiration was assumed to average 0.1 inch per day. Water in the top 6 inches of the soil was assumed to be lost at the rate of 0.1 inch per day, and meteorological factors affecting water loss were ignored. On clear days, there is a large amount of energy available for evaporation. As long as capillary films can supply moisture to meet the evaporative demand, evaporation is limited by the energy available. Once these films cannot supply adequate moisture, the availability of moisture becomes the limiting factor. Lemon (6) stated that this condition occurs as a bare-field soil approaches field capacity. Philip (10) showed that this occurred about 3 days after the soil had been saturated. Penman (8) has demonstrated that, the lower the evaporative demand, the lower is the moisture content at the critical point. On cloudy days, energy may be the limiting factor. The use of 0.1 inch loss per day gave excellent results for the period concerned, and no modification was attempted. This rate, which seems realistic for Iowa for this period, may have to be modified for other areas.

June 7 through Sept. 30

As the corn plant grows, considerable change takes place in the ground cover produced by the crop. June 7 was selected as the date when the prediction technique was changed for two reasons:

(1) A noticeable change is taking place in the ratio of evapotranspiration to open-pan evaporation at this time, and (2) it is the start of a week in the standard climatological year.

Commencing June 7, open-pan evaporation was used as the starting point for estimating evapotranspiration. Data for Iowa and surrounding states were plotted, and isolines of the average daily pan evaporation in inches were drawn for each week. A typical example is shown in fig. 3. Although daily values might have been more con-

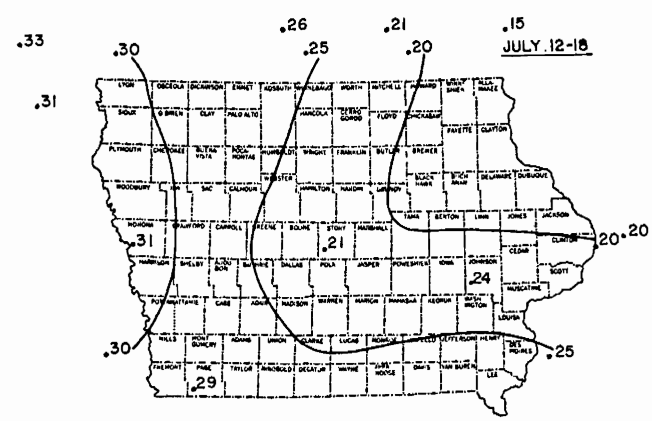

Fig. 3. Map showing isolines of average daily open-pan evaporation in inches per day, for week of July 12-18, 1960.

[4] This date coincides with the end of a standard climatological week, where week 1 is March 1-7.

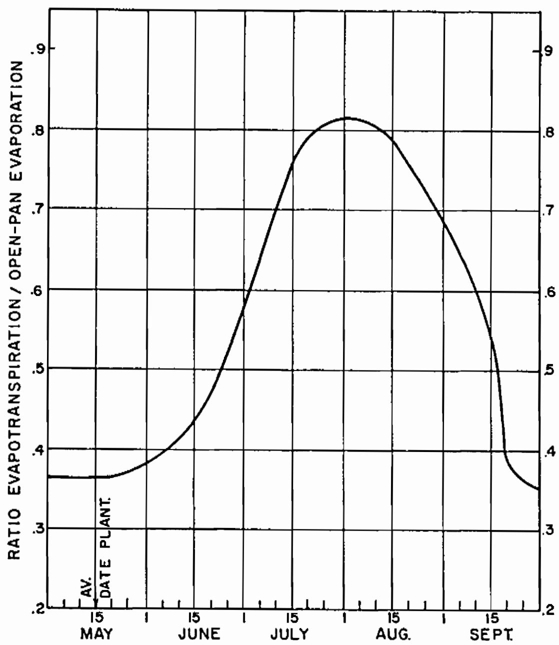

Fig. 4. Ratio of evapotranspiration of corn to open-pan evaporation throughout the growing season (after Denmead and Shaw, 3). On the average, 50 percent of the corn in Iowa is silked by July 31.

cise, an average value of daily evapotranspiration was computed for each weekly period to facilitate computation. The weekly average of daily pan evaporation for each sampling site was read from the isoline map, and this value then was multiplied by a factor to adjust evapotranspiration to the proper stage of crop development. This factor was obtained from fig. 4. The curve in fig. 4 represents conditions where surface moisture may limit evaporation but moisture in the root zone does not limit evapotranspiration (3). The calendar dates used on this figure represent the average date of occurrence in Iowa of the phenological events shown. For very early or late crop development, the calendar dates should be adjusted to fit the phenological dates. The product of these two values (pan evaporation in inches x crop development factor in percent) gives the evapotranspiration in inches when soil moisture is not limiting.

Data obtained by Denmead and Shaw (4) show that, under conditions of high atmospheric demand, transpiration from a plant will decrease at a relatively high soil-moisture content because the plant cannot supply water fast enough to meet the high demand. At low atmospheric demand there will be no reduction in water loss until a relatively low soil-moisture content is reached. The Denmead and Shaw data were collected by using lysimeters, which restricted root development, and the data represent only transpiration. In the field from June to August, the root zone is continually advancing, representing a stress condition different from that in a lysimeter, and the water loss in the field is both by evaporation and transpiration.

Three curves were selected from Denmead and Shaw's (4) data to represent different stress days. The high-stress curve used represents a transpiration rate of 0.22 inch per day. Days when pan evaporation was above 0.30 inch were classed as high-stress days. Days when pan evaporation was between 0.20 inch and 0.30 inch were classed as average, and the curve used represents a transpiration rate of 0.16 inch per day. Days when pan evaporation was less than 0.20 inch were classed as low-demand days, and the curve used represents a transpiration rate of 0.08 inch per day. These three curves are shown in fig. 5. The percent of available water in the root zone was used for entry on the horizontal axis. The relative evapotranspiration rate was read from the vertical axis. Data for Ames for a 23-year period show that these pan-evaporation values have occurred at the frequencies shown in table 2. These frequencies would vary widely among different climates.

Rooting depth was considered to be as follows: to June 27, 2 feet; to July 4, 2½; to July 11, 3; to July 18, 3½; to July 25, 4; to Aug. 1, 4½; and after Aug. 1, 5 ft. Because of the sparse plant cover and the relatively low ratio of evapotranspiration to open-pan evaporation, no stress was

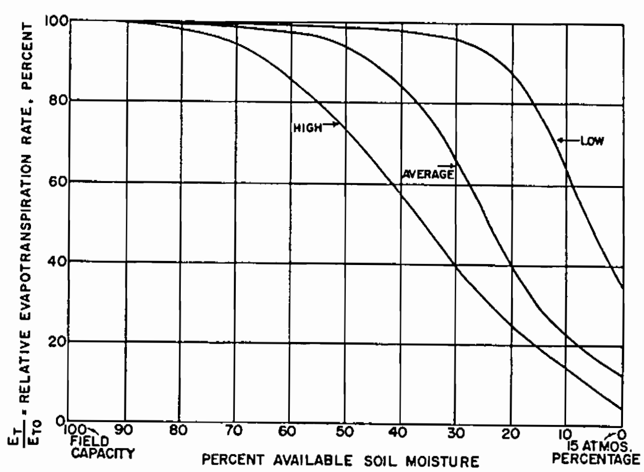

Fig. 5. Relative evapotranspiration rates for different atmospheric demand rates prior to Aug. 1. E_T is actual evapotranspiration, E_{TO} is open-pan evaporation (after Denmead and Shaw, 4).

Table 2. Percent occurrence of daily open-pan evaporation at Ames, Iowa in high, medium and low classifications during June, July and August, 1933-55.

Level of daily pan evaporation	Percent of total days in each month when pan-evaporation occurred at specified levels.		
	June	July	August
High (> 0.30″)	26	44	41
Medium (0.20 - 0.30″)	39	41	14
Low (< 0.20″)	35	15	45

Table 3. **Field capacity and available soil moisture on July 18, 1959, for Castana, Iowa. Values given are for the top 5 feet of soil, by 1-foot increments.**

Depth (ft.)	Field capacity (inches)	Available moisture on July 18 (inches)
0-1	2.5	0.8
1-2	2.0	0.0
2-3	2.0	1.2
3-4	2.0	1.4
4-5	2.0	1.5

assumed to occur before June 27 as long as any water was available in the root zone.

The available soil moisture was determined as a percentage of field capacity in the root zone for each week. To determine the percentage of field capacity for a given week, the amount of water in the profile to the depth to which roots advanced during the week was used. For example, for the period July 18-25, roots advanced to 4 feet (table 3). The percentage of field capacity for this week was:

$$\frac{0.8 + 0.0 + 1.2 + 1.4}{2.5 + 2.0 + 2.0 + 2.0} = \frac{3.4}{8.5} = 40 \text{ percent.}$$

To simplify the computations, the value computed in this manner was used as the percentage of field capacity available for the entire week. The daily average open-pan evaporation was 0.32 inch; therefore, the high atmospheric stress curve was used. From fig. 5, the relative evapotranspiration was found to be 58 percent, since only 40 percent of field capacity was present.

Evapotranspiration per day, then, is equal to:

Pan evaporation (fig. 3) x ratio for crop development (fig. 4) x stress factor (fig. 5) = 0.32 x 0.78 x 0.58 = 0.14 inch, instead of the 0.25 inch that would have resulted if no stress were present.

Roots were assumed to reach a depth of 5 feet by Aug. 1. Since little further penetration would occur, a different effect of atmospheric stress appeared evident. A different set of curves (fig. 6) was used after July 31. Use of these curves resulted in a greater reduction in evapotranspiration for a comparable stress, compared with the period before Aug. 1 when the roots were advancing.

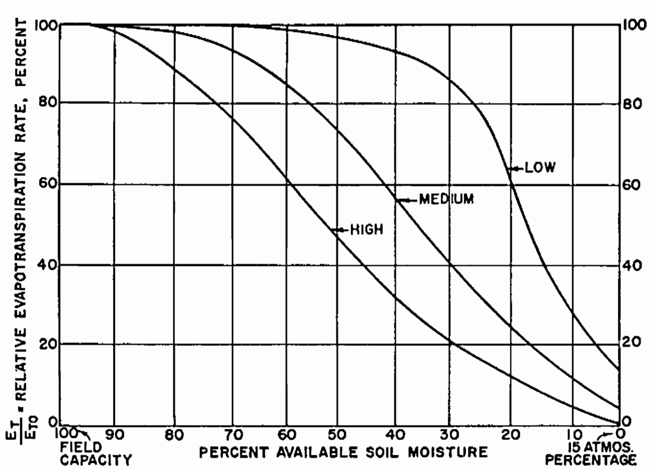

Fig. 6. **Relative evapotranspiration rates for different atmospheric demand rates after Aug. 1. E_T is actual evapotranspiration, E_{TO} is open-pan evaporation (after Denmead and Shaw, 4).**

Water was assumed to be removed from each foot-increment in the pattern shown in table 4. When an increment of soil did not have available water, the water that would have been used from that increment was moved to the other depths from which water was being extracted. When an increment of soil other than the top foot had no available water, the amount was prorated among the other depths from which water was being extracted. When the top foot had no available water, the extraction pattern was shifted one depth deeper. The amount normally extracted from the deepest active depth was divided equally among the other active depths. For example, from July 12 to 18, the water use would normally be 60, 15, 15 and 10 percent from the 1st, 2nd, 3rd and 4th foot-increments, respectively. With no available water in the top foot, the amounts would be 0, 60 plus 1/3 of 10 percent, 15 plus 1/3 of 10 percent and 15 plus 1/3 of 10 percent, or, with rounding 0, 63, 18 and 18 percent from the 1st, 2nd, 3rd and 4th foot-increments, respectively.

Another factor had to be considered for days when the transpiration loss was reduced because of moisture stress. If recent rains had added water to the soil, higher evaporation would be taking place. As long as this water was present in the top 6 inches, up to 0.1 inch per day evaporation could take place. For example, on the day when the potential rate was 0.25 inch, loss would be 0.14 inch if no available water were present in the top 6 inches, but loss would be 0.24 inch (0.14 + 0.10) if water were available. The amount of water lost by evaporation could not bring the total amount lost above the potential rate.

Table 4. **Water extraction from the soil profile at different depths during the growing season. Values for each date are given as the percentage of evaporation or evapotranspiration that occurs from each of the depths listed.**

Dates	Percent of E or ET which comes from respective depths	Depths from which water was extracted
to June 7	100	1st 6 inches
June 8 to 14	100	1st foot (equally from each 6 inches)
June 15 to 27	67.7, 33.3	1st, 2nd foot
June 28 to July 4	60, 20, 20	1st, 2nd and top half of 3rd foot
July 5 to 11	60 20, 20	1st, 2nd and 3rd foot
July 12 to 18	60, 15, 15, 10	1st, 2nd, 3rd and top half of 4th foot
July 19 to 25	60, 15, 15, 10	1st, 2nd, 3rd and 4th foot
July 26 to Aug. 1	60, 10, 10, 10, 10[a]	1st, 2nd, 3rd, 4th and upper half 5th foot
	60, 15, 15, 10[b]	1st, 2nd, 3rd and 4th foot
After Aug. 1	60, 10, 10, 10, 10[a]	1st, 2nd, 3rd, 4th and 5th foot
	60, 15, 15, 10	1st, 2nd, 3rd and 4th foot

[a] Used only if first 4 feet all have $<$ 50 percent available moisture.
[b] Used if any of first 4 feet have $>$ 50 percent available moisture; however, after Aug. 1, the percent available is always computed on the total available water in the 5-foot profile.

Table 5. Computation sheet for April to June soil moisture, sampled April 9 and June 8, Ames, 1955 (all values are in acre inches).

Depth (feet)	Field capacity	Available moisture by climatological weeks											
		Avail. Apr. 9[a]	Avail. Apr. 11	Avail. Apr. 18	Avail. Apr. 25	Avail. May 2	Avail. May 9	Avail. May 16	Avail. May 23	Avail. May 30	Avail. June 6	Avail. June 8	Avail. June 8
												(est.)	(actual)
0-½	0.9	0.4	0.3	0.5	0.8	0.1	0.9	0.2	0.2	0.7	0.5	0.3	1.0
½-1	0.9	0.4	0.4	0.7	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	1.3
1-2	1.6	0.8	0.8	0.8	1.5	1.5	1.6	1.6	1.6	1.6	1.6	1.6	1.4
2-3	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6
3-4	1.6	1.5	1.5	1.5	1.5	1.5	1.6	1.6	1.6	1.6	1.6	1.6	1.5
4-5	1.6	1.6	1.6	1.6	1.6	1.5	1.6	1.6	1.6	1.6	1.6	1.6	1.5
		6.3	6.2	6.7	7.9	7.1	8.2	7.5	7.5	8.0	7.8	7.6	7.3

Water Balance

Date	P[b]	R	E
Apr.			
10	0	0	0.1
11	0.1	0	0.1

Date	P	R	E
Apr.			
12	0.2	0	0.1
13	0.9[c]	0	0.1
14	0.1	0	0.1
15	0	0	0.1
16	0	0	0.1
17	0	0	0.1
18[e]	0	0	0.1

Date	P	R	E
Apr.			
19	0.3	0	0.1
20	0	0	0.1
21	0	0	0.1
22	0	0	0.1
23	1.4[d]	0.2	0.1
24	0.4	0	0.1
25	0	0	0.1

Date	P	R	E
Apr.			
26	0	0	0.1
27	0	0	0.1
28	0	0	0.1
29	0	0	0.1
30	0	0	0.1
May			
1	0	0	0.1
2	0	0	0.1

Date	P	R	E
May			
3	0.2	0	0.1
4	0.5	0	0.1
5	0	0	0.1
6	0.2	0	0.1
7	0	0	0.1
8	0	0	0.1
9	1.9	0.4	0.1
	(0.6″ perc.)[f]		

Date	P	R	E
May			
10	0	0	0.1
11	0	0	0.1
12	0	0	0.1
13	0	0	0.1
14	0	0	0.1
15	0	0	0.1
16	0	0	0.1

Date	P	R	E
May			
17	0	0	0.1
18	0	0	0.1
19	0	0	0
20	0	0	0
21	0	0	0
22	0	0	0
23	0.2	0	0[g]

Date	P	R	E
May			
24	0	0	0.1
25	0	0	0.1
26	0.6	0	0
27	0	0	0.1
28	0.6	0	0.1
29	0	0	0.1
30	0	0	0.1

Date	P	R	E
May			
31	0	0	0.1
June			
1	0	0	0.1
2	0	0	0.1
3	0	0	0.1
4	0.5	0	0.1
5	0	0	0.1
6	0	0	0.1

Date	P	R	E
June			
7	0	0	0.1
8	0	0	0.1

[a] April 9 moisture in top 6 inches was 0.8/2 = 0.4 inch.

[b] P = precipitation, R = runoff and E = evaporation.

[c] No runoff on April 13 = net gain of 0.8 inch. Top 6 inches had 0.3″ on 11th, 0.4″ on 12th because of gain of 0.1. On 13th evaporation of 0.1″ reduces this to 0.3″ so it will hold 0.6″ more, bringing it to 0.9″; remaining 0.3″ added to next deeper layer.

[d] $API = 0/1 + 0/2 + 0/3 + 0.3/4 + \ldots + 0.1/9 + 0.9/10 + 1.4/2 = 0.87$. From fig. 1, at intersection of 1.4 inches of rainfall and API of 0.87, runoff = 0.2″. Moisture in top 6 inches was 0.3″ after evaporation on 23rd, and 0.6″ was used to bring it to field capacity. Of the 0.6″ which percolated through the top 6 inches, 0.2″ was used to fill the second 6″ to field capacity and 0.4″ moves to next layer. 0.3″ percolated through top foot on 24th to bring second foot up to 1.5″ available water.

[e] April 18, moisture in top 6 inches was reduced from 0.9″ after rain on 13th to 0.5″ on 18th.

[f] Gain on May 9 was greater than capacity of soil; 0.6″ percolated through profile.

[g] No evaporation this day because evaporation was subtracted before adding in precipitation, and none was available before precipitation occurred.

Table 6. Sample computation sheet for June to late July soil moisture, sampled June 4 and July 31, Northwest Iowa Experimental Farm, 1958 (all values in acre inches).

Depth (feet)	Field capacity	Available moisture by climatological weeks										
		Avail. June 4	Avail. June 6	Avail. June 13	Avail. June 20	Avail. June 27	Avail. July 4	Avail. July 11	Avail. July 18	Avail. July 25	Avail. July 31	Avail July 31
											(est.)	(actual)
0-½	1.3	1.1	0.8	0.7	0.4	1.2	1.3	1.1	0.8	0.5	1.1	{ 0.8
½-1	1.2	1.1	1.1	0.8	0.6	0.8	1.0	1.1	0.8	0.5	0.2	
1-2	2.0	1.4	1.4	1.4	1.1	0.8	0.5	0.7	0.5	0.3	0.1	0.2
2-3	2.0	1.4	1.4	1.4	1.4	1.4	1.1	0.9	0.8	0.6	0.4	0.6
3-4	2.0	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.1	1.0	1.0	0.8
4-5	2.0	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.7
		7.1	6.8	6.4	5.6	6.3	6.0	5.9	4.9	3.8	3.7	3.1

Water Balance

Date	P[a]	R	ET[b]	Date	P	R	ET[c]	Date	P	R	ET[d]	Date	P	R	ET[e]	Date	P	R	ET[f]	Date	P	R	ET[g]	Date	P	R	ET[h]	Date	P	R	ET[i]	Date	P	R	ET[j]
June				June				June				June				June				July				July				July				July			
4	0	0	0.1	7	0	0	0.1	14	0	0	0.12	21	0	0	0.11	28	0	0	0.21	5	0	0	0.16	12	0	0	0.14	19	0	0	0.17	26	0	0	0.16
5	0	0	0.1	8	0	0	0.1	15	0	0	0.12	22	1.2	0.2	0.11	29	0	0	0.21	6	0	0	0.16	13	0	0	0.14	20	0.1	0	0.17	27	0.7	0	0.16
6	0	0	0.1	9	0	0	0.1	16	0	0	0.12	23	0.3	0	0.11	30	0	0	0.21	7	0	0	0.16	14	0	0	0.14	21	0	0	0.17	28	0.2	0	0.16
																July																			
				10	0	0	0.1	17	0	0	0.12	24	0.2	0	0.11	1	0	0	0.21	8	0.8	0	0.16	15	0	0	0.14	22	0	0	0.17	29	0	0	0.16
				11	0.1	0	0.1	18	0	0	0.12	25	0	0	0.11	2	0.1	0	0.21	9	0.2	0	0.16	16	0	0	0.14	23	0	0	0.17	30	0	0	0.16
				12	0	0	0.1	19	0	0	0.12	26	0	0	0.11	3	0.9	0	0.21	10	0	0	0.16	17	0	0	0.14	24	0	0	0.17	31	0	0	0.16
				13	0.2	0	0.1	20	0	0	0.12	27	0	0	0.11	4	0.2	0	0.21	11	0	0	0.16	18	0	0	0.14	25	0	0	0.17				

[a] P = precipitation, R = runoff, ET = evapotranspiration.

[b] ET for this week was assumed to be 0.1″/day.

[c] ET = average daily pan-evaporation x crop cover factor = 0.24 x 0.41 = 0.10.″ No stress present.

[d] ET for week = 0.27 x 0.45 = 0.12; 0.12 x 7 = 0.84″ which, with rounding is 0.8.″ If balance is computed for each day, subtract 0.2″ for first day and 0.1″ on last 6 days to allow for ET of 0.8″/ week. Of the water used, 2/3 comes from top foot, equally from each 6-inch increment, and 1/3 from 2nd foot.

[e] ET = 0.22 x 0.5 = 0.11; 0.11 x 7 = 0.77 = 0.8. Use from top 2 feet, same as in footnote c. 0.4″ percolates to 2nd 6 inches of top foot from rains on June 22, 23 and 24.

[f] Root development to July 4 is 2½ ft. Percent available moisture = $\frac{(2.0 + 0.8 + 0.7)}{(2.5 + 2.0 + 1.0)} = \frac{3.5}{5.5}$ = 64 percent. Divide 1.4 by 2 to get moisture from 2 to 2½ ft.

For a high-demand period (pan > 0.30″), adjusted ET = 91 percent (0.21 x 0.91 = 0.19″/day). However, there is water available in top 6 inches for evaporation, and this brings ET back to 0.21″/day. Use is 60, 20 and 20 percent from 1st, 2nd and 3rd foot-increments. Percolation of 0.6″ through 1st 6 inches.

[g] Average-demand period and no stress, so ET occurs at maximum rate (0.16 x 7) = 1.12; Use 60, 20 and 20 percent from 1st, 2nd and 3rd foot-increments. Percolation through top 6 inches of 0.6″ on 8th and 0.2″ on 9th. Percolation through 2nd 6-inch increment of 0.2″ on both 8th and 9th.

[h] Low-demand period, no stress, 0.14 x 7 days = 0.98 = 1.0″ loss for week. Use is 60, 15, 15 and 10 percent from 1st, 2nd, 3rd and 4th foot, respectively.

[i] Average-demand period. Root depth to 4 feet by July 25. Percent available water in root zone is 4.0/8.5 = 49 percent. ET is 92 percent of potential = 0.17 x 0.92 = 0.16,″ but since water available in top 6 inches, use is 0.17″ per day.

[j] Low-demand period. Percent available = 40 percent. ET = 0.16 x 0.98 = 0.16. Use is 60, 15, 15 and 10 percent from 1st, 2nd, 3rd and 4th feet since all increments not < 50 percent available.

Oct. 1 and later

Transpiration was assumed to cease Oct. 1—unless terminated earlier by a killing frost or unless delayed plant development indicated that transpiration should continue later. After Oct. 1, evaporation (or evapotranspiration when it occurred) was assumed to be 0.35 of pan evaporation. This value was estimated from fig. 4. The energy available for evaporation in October and November is low, and the potential for evaporation was considered the best factor for estimating the loss. Evaporation was assumed to occur only from the top 6 inches. After Nov. 1, when evaporation-pan data were not available, evaporation was assumed to be 0.1 inch per week.

Summary of Steps Required in Computing Soil-Moisture Balance

1) Set field-capacity and wilting-point values for each increment of soil and determine the plant-available water for each increment.
2) Start with measured soil moisture in the profile on first date of sampling. For the first 3 days, consider excess water in profile resulting from recent rains.
3) Subtract evaporation, evapotranspiration, or both, for each day.
4) Add daily precipitation after adjusting for runoff.

Sample computation sheets are shown in table 5 for the April-June period and in table 6 for the June-August period. The top part of each table shows the available moisture at the end of each week, so that the procedure for each week can be checked.

RESULTS AND DISCUSSION

April-June Period

Comparison of observed and predicted total available moisture in the profile

The results obtained applying this procedure to soil-moisture data for the 1954-60 period are shown in fig. 7. Very good agreement was obtained between the observed and predicted soil moisture as shown by a correlation for all years of 0.96. The correlation coefficients for each year were near 0.90 or higher and were significant at the 1-percent level—except for 1954 when, with only 6 comparisons, the correlation of 0.88 was significant at the 5-percent level. The linear regression for all years was

$$Y = 0.49 + 0.94X \qquad (3)$$

where the observed soil moisture is X and the predicted soil moisture, Y. Although there was

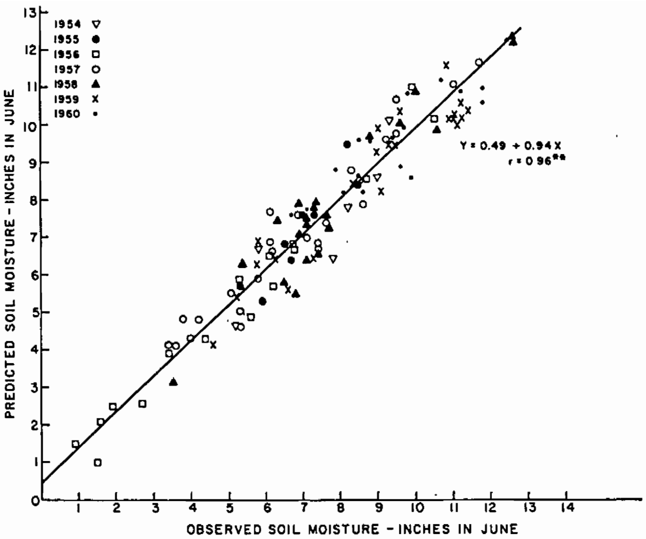

Fig. 7. Comparison of observed and estimated soil moisture, inches in June, 1954-60.

a close relationship between the observed and predicted value, because of the large sample size, 0.94 differs from 1.00, and 0.49 differs from 0, between the 5- and 1-percent levels of probability. The standard deviation from regression was 0.70 inch, which compares favorably to the variation found in the soil-moisture sampling.

In use, this regression equation would be used as a calibration curve to predict an X value from a Y value. The soil-moisture value, Y, obtained by the prediction technique would be used to obtain a calibrated, or adjusted, X value from the regression equation.

Comparison of errors in prediction in each foot-increment

In some situations, the distribution of the soil moisture within the profile is very important. Although the total moisture in the profile was generally predicted within 1 inch of the observed moisture, this does not show how well the distribution within the profile was predicted. The differences between the observed soil moisture and the predicted value for each foot-increment are summarized in table 7. The top foot was underestimated an average of 0.13 inch, while the second foot was overestimated 0.16 inch.

Table 7. Average difference and standard deviation of difference between predicted and observed June soil moisture and percentage of errors > 1 inch and ⩽ 0.5 inch.

Depth (feet)	Average difference (inches)	Std. dev. of diff. (inches)	Errors > 1 inch (percent)	Errors of 0.5 inch or less (percent)
0-1	−0.13	0.46	6.9	79.1
1-2	+0.16	0.34	0.0	80.0
2-3	+0.10	0.38	1.7	79.3
3-4	−0.03	0.35	0.9	91.0
4-5	−0.05	0.32	0.9	91.4
0-5	+0.05	....	8.6	50.0

For the three deeper depths, the predicted value averaged 0.10 inch or less from the observed value. The standard deviation of the difference between the observed and predicted value, was largest in the top foot, 0.46 inch, and about 1/3 inch for the other depths. There were relatively few errors greater than 1 inch, with a high percentage of the errors for each foot-increment being less than 0.5 inch. For the 5-foot profile, 50 percent of the errors were 0.5 inch or less and only 8.6 percent were over 1 inch.

Rating of predicted values

An attempt was made to rate the predicted value as to distribution in the profile and difference in the total amount of moisture in the profile. Although arbitrary, such a rating system provides a quick method of examining the results. The ratings used are:

1. Each foot-increment within ½ inch of observed value.
2. Four within ½ inch, one within ½ to 1 inch of observed value.
3. Four within ½ inch, one more than 1 inch different from observed value.
4. Three within ½ inch, two within 1 inch of observed value.
5. Three within ½ inch, one within 1 inch, one more than 1 inch different from observed value.
6. All within 1 inch of observed value.
7. Others.

Each group was further classified as to the total soil moisture in the profile as follows:

a) Total within 1 inch of observed value.
b) Total 1 inch or more different from observed value.

On the basis of these ratings, the accuracy of predicting the distribution within the profile is shown in table 8.

Table 8. Rating of soil-moisture prediction for the spring period.

Rating	Number of occurrences	Percent
1a[a]	53	46.1
1b	3	2.6
2a	30	26.1
2b	6	5.2
3a	5	4.3
3b	1	0.9
4a	11	9.6
4b	0	0
5a	2	1.8
5b	0	0
6a	4	3.4
6b	0	0
7a	0	0
7b	0	0

[a] Ratings defined in text.

June-August Period

Comparison of observed and predicted total available moisture in the profile

In 1954, moisture samples were taken each month. The results are included here for comparison with the results obtained for the June-August period in other years. Although the 1954 data are for only 1 year, the results indicate the consistency of the prediction technique for shorter periods within the longer period. The correlation between predicted and observed total soil moisture for the June period was 0.96. The linear regression was

$$Y = -0.05 + 1.00X \qquad (4)$$

where X is the observed value, and Y the predicted value. For the July period the correlation was 0.98. The linear regression was

$$Y = 0.28 + 0.93X. \qquad (5)$$

Only 16 comparisons were available for this period, and 0.93 did not test statistically different from 1.00, nor was 0.28 different from 0.

For the June-August period, the correlations were computed for each year, except 1954 which was divided into the two periods already presented. The correlations for each year were near 0.90 or higher and were significant at the 1-percent level. For all years the correlation was 0.95. The comparison between the observed and predicted values for 1955-60 is shown in fig. 8. The linear regression equation for all years was

$$Y = 0.34 + 0.94X \qquad (6)$$

with 0.94 being significantly different from 1.00, and 0.34 significantly different from 0, between the 5-percent and 1-percent limits of probability. The standard deviation from regression was 0.84 inch.

Comparison of errors in prediction in each foot-increment

A summary of the differences between the observed and predicted soil moisture for each foot-

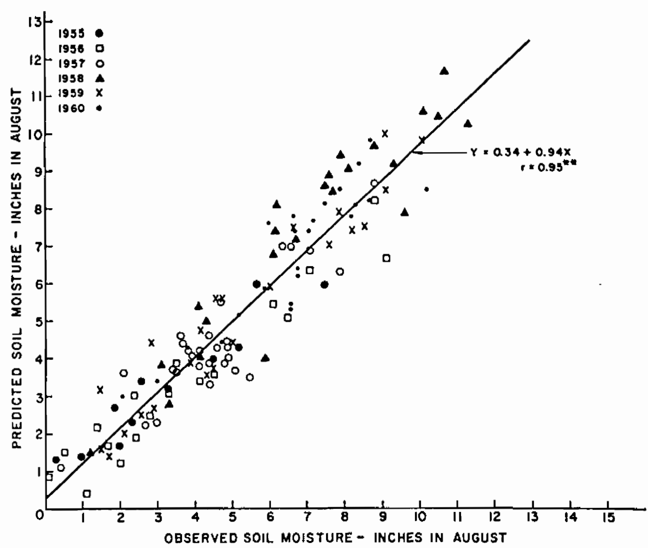

Fig. 8. Comparison of observed and estimated soil moisture, inches in August, 1954-60.

Table 9. Average difference and standard deviation of difference between predicted and observed August soil moisture and percentage of errors > 1 inch and ≤ 0.5 inch.

Depth (feet)	Average difference (inches)	Std. Dev. diff. (inches)	Errors > 1 inch (percent)	Errors of 0.5 inch or less (percent)
0-1	−0.10	0.38	2.4	83.1
1-2	−0.05	0.53	5.4	77.7
2-3	+0.02	0.43	1.5	86.9
3-4	+0.06	0.36	0.9	84.6
4-5	+0.09	0.36	2.4	84.8
0-5	+0.02	....	19.8	47.5

Table 10. Rating of soil-moisture prediction for the summer period.

Rating	Number of occurrences	Percent
1a[a]	55	42.3
1b	9	6.8
2a	23	17.7
2b	11	8.5
3a	7	5.4
3b	3	2.3
4a	8	6.2
4b	2	1.5
5a	3	2.3
5b	2	1.5
6a	3	2.3
6b	0	0
7a	2	1.5
7b	2	1.5

[a] Ratings defined in text.

increment is given in table 9. The two top feet were estimated low, and the three lower feet estimated high, but all averaged 0.10 inch or less from the observed values. The predicted mean soil moisture in the 5-foot profile was very close to that observed. Errors greater than 1 inch were few for the individual foot increments, and 80 percent of the errors were less than 0.5 inch in each foot. For the 5-foot profile, approximately 50 percent of the values were within 0.50 inch.

Rating of predicted values

Based on the same ratings used for the spring period, the accuracy of the prediction technique is shown in table 10. Sixty percent of the values were in either the 1a or 2a classes, about 12 percent less than for the spring period.

August-November Period

Comparison of observed and predicted total available moisture in the profile

In 1954, samples were taken in early August, early September, late September or early October, and early November. For the period of early August to early September the correlation between the predicted and observed soil moisture was 0.96. The linear regression was

$$Y = 0.65 + 0.85X. \qquad (7)$$

The regression coefficient 0.85, was statistically different from 1.00, and 0.65 was different from 0, at the 5-percent level of significance.

For the September period, the correlation between the predicted and observed soil moisture was 0.97. The linear regression was

$$Y = 0.19 + 0.98X. \qquad (8)$$

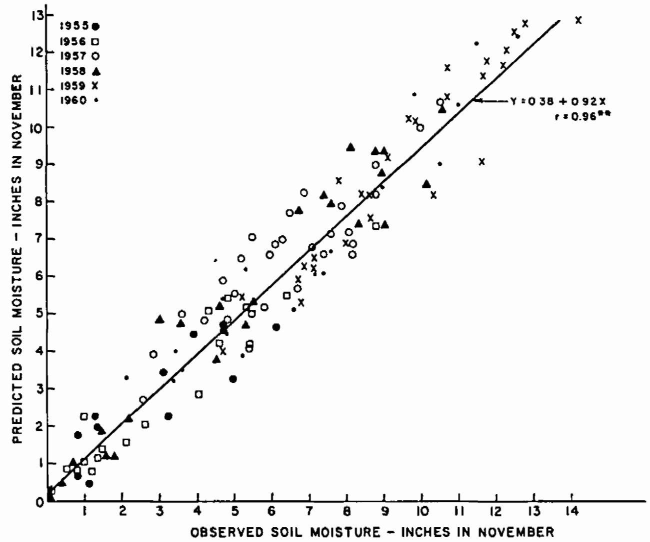

Fig. 9. Comparison of observed and estimated soil moisture, inches in November, 1954-60.

For the late September-November period the correlation between the predicted and observed soil moisture was 0.98. The linear regression was

$$Y = 0.41 + 0.98X. \qquad (9)$$

For the years 1955-60, samples were taken only in early August and early November. The correlation between actual and predicted soil moisture was 0.96. Correlations for individual years were all highly significant. The linear regression (fig. 9) for 1955-60 was

$$Y = 0.38 + 0.92X. \qquad (10)$$

The regression coefficient, 0.92, was different from 1.00 at the 1-percent level of probability, and 0.38 was different from 0 at the 5-percent level of probability. The standard deviation from regression was 0.85 inch.

Comparison of errors in prediction in each foot

A summary of the differences between the observed and predicted soil moisture for each foot-increment is given in table 11. All values averaged within 0.10 inch of the observed value. The standard deviation of the difference between the observed and the predicted values ranged from 0.4 inch to 0.5 inch. More than 80 percent of the

Table 11. Average difference and standard deviation of difference between predicted and observed November soil moisture and percentage of errors > 1 inch and ≤ 0.5 inch.

Depth (feet)	Average difference (inches)	Std. dev. diff. (inches)	Errors > 1 inch (percent)	Errors of 0.5 inch or less (percent)
0-1	−0.06	0.48	3.6	83.0
1-2	−0.08	0.50	4.3	82.0
2-3	−0.04	0.49	3.6	82.8
3-4	+0.01	0.42	0.7	82.4
4-5	+0.07	0.39	2.1	84.9
0-5	−0.10	....	23.7	42.4

values in each foot-increment were 0.5 inch or less from the observed value.

Rating of predicted values

On the basis of the same ratings used previously, the ratings for the fall prediction are summarized in table 12. About 60 percent were in the 1a or 2a classes, which was lower than for the spring period but about the same as for the summer period.

Table 12. Rating of soil-moisture prediction for the fall period.

Rating	Number of occurrences	Percent
1a[a]	50	36.0
1b	12	8.6
2a	34	24.5
2b	8	5.8
3a	7	5.0
3b	4	2.9
4a	10	7.2
4b	2	1.4
5a	0	0.0
5b	3	2.1
6a	2	1.4
6b	3	2.1
7a	2	1.4
7b	2	1.4

[a] Ratings defined in the text.

CONCLUSIONS

Over-all, the method of prediction developed here is considered very successful. In predicting soil moisture under a row crop such as corn, it must be expected that the method will require several steps in its computation. This is because the potential evapotranspiration values must be modified to take into account crop cover and moisture availability. The results indicated that the procedure can be used for a wide range of weather conditions and may be applicable to areas other than Iowa if the rooting pattern of corn is similar. Runoff amounts may vary with the soil type and particularly with the amount of slope. The constants of the regression equations would not necessarily be the same.

Further refinements could be made in the procedure developed here. However, additional adjustments further complicate the computation, and the effort expended may not be worth the gain in accuracy obtained.

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